

Inner Polar Rings and Disks: Observed Properties

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Abstract. A list of galaxies with inner regions revealing polar (or strongly inclined to the main galactic plane) disks and rings is compiled from the literature data. The list contains 47 galaxies of all morphological types, from E to Irr. We consider the statistics of the parameters of polar structures known from observations. The radii of the majority of them do not exceed 1.5 kpc. The polar structures are equally common in barred and unbarred galaxies. At the same time, if a galaxy has a bar (or a triaxial bulge), this leads to the polar disk stabilization — its axis of rotation usually coincides with the major axis of the bar. More than two thirds of all considered galaxies reveal one or another sign of recent interaction or merging. This fact indicates a direct relation between the external environment and the presence of an inner polar structure.

1. INTRODUCTION

When we generally talk about the presence in a galaxy of subsystems rotating in mutually orthogonal planes, we mean the so-called polar ring galaxies (PRG). The central galaxy here (typically, of an early-type, E/S0) is surrounded by an external ring or even by a stellar-gaseous disk, sized up to several tens of kiloparsecs, positioned roughly perpendicular to the galactic plane. The first studies of the internal kinematics of PRGs date back to the late 1970s, while their mass study began after the publication by Whitmore et al. (1990) of a photographic catalog of PRG candidates. Despite the lack of detailed data on the dynamics, evolution and history of star formation in the PRGs, the key issues can now be considered solved. In the presence of a triaxial or spheroidal dark halo, polar orientation is stable with respect to the differential precession, so that the ring can make a lot of revolutions around the central galaxy undisturbed. Numerical models demonstrate that the PRGs are the result of interaction with the surrounding matter, the moment of rotation of which is perpendicular to the rotation axis of the galaxy. The basic mechanisms usually discussed are the capture of matter from the donor galaxy, the merger of two orthogonally oriented disks, and for the most massive and extended rings—accretion of gas from the intergalactic filaments (see references in Combes (2006) review).

Despite the relatively rare occurrence among the nearby galaxies, the phenomenon of external polar rings is widely known. At the same time, the literature describes the cases of inner polar rings and disks, usually scaled below one kiloparsec. This phenomenon is more poorly stud-

ied, which may as well be explained by the lower “clarity” of such structures, usually invisible in the optical images of galaxies in contrast to the “classical” PRGs. It requires quite a lot of effort to identify the internal polar or inclined disk against the bright bulge, and especially to obtain detailed data on the motions of the gaseous and stellar components in the central regions of galaxies.

Interestingly, the inner polar structures (IPS) were known even before the phenomenon of PRG has been recognized and confirmed. For instance, during the spectral observations of the Sc galaxy NGC 3672 a significant gradient of the line-of-sight velocities along its minor axis was detected (Rubin et al., 1977). According to the authors, this indicates that the axis of rotation of the circumnuclear ($r < 350$ pc) gas has a considerable angle with the axis of rotation of the galaxy. The alternative explanation proposed—compression of the gaseous disk in the galactic plane—seems to be less convincing. Later Bettoni et al. (1990), according to the results of the long-slit spectroscopy of NGC 2217 have shown that within the central kiloparsec, a disk of ionized gas is warped in such a way that rotation occurs in the plane, perpendicular to the stellar disk of the galaxy. Moreover, the axis of rotation of this polar disk practically coincides with the major axis of the stellar bar of NGC 2217. In the following decade, similar kinematically decoupled structures were found by several authors within the detailed studies of internal kinematics of other nearby early-type galaxies. Note, first of all, the researches made by Olga Sil’chenko and her colleagues at the 6-m BTA telescope of the Special Astrophysical Observatory of Russian Academy of Sciences (SAO RAS) using the methods of panoramic (3D) spectroscopy (Sil’chenko et al., 1997; Sil’chenko & Afanasiev, 2000; Sil’chenko, 2002), as well as

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the publications related with the group of the University of Padua (Bertola & Corsini, 2000; Pizzella et al., 2001). The list of galaxies with confirmed IPSs, published in 2003, already contained 17 objects (Corsini et al., 2003). In the subsequent decade, various groups have presented a fairly extensive observational material, dedicated to the detection and investigation of such structures. This was much facilitated by the survey of kinematics and stellar population of nearby early-type galaxies, performed at the 4.2-m WHT telescope, and the study of chemically decoupled galactic nuclei at the SAO RAS 6-m BTA telescope, performed using the SAURON and MPFS integral-field spectrographs, respectively. The study by Sil'chenko & Afanasiev (2004) is also representative. Here, the authors selected for the MPFS observations eight galaxies, the optical images of the central regions of which are clearly revealing the dust lanes, projected onto the nucleus, which argues in favor of the presence of gas-dust disks, strongly inclined to the line of sight. The derived velocity fields of ionized gas and stars have confirmed the existence of internal disks or polar rings in all the sample objects. Coccato et al. (2004) have demonstrated that in 50–60% of bright unbarred galaxies the remarkable gradient of the line-of-sight velocity is observed along the minor axis, which may partly be explained by the presence of IPSs. In Moiseev et al. (2010) we briefly presented a new list of 37 galaxies with IPSs. Despite the fact that the number of such objects surpasses the number of kinematically confirmed external polar rings, their nature remains vague. Up to date, there is no clear self-consistent scenario of their formation, the issues of stability of such structures are not resolved either. The views on the relationship of IPSs with bars of galaxies and their external environment (the presence of companions, traces of interaction, etc.) are contradictory (Corsini et al., 2003; Moiseev et al., 2010).

This paper presents an updated list of galaxies with inner polar rings and disks, compiled based on the data published in the literature, including our own observational data obtained with the 6-m telescope. A large enough number of objects allowed us to consider some statistical relations in the properties of IPSs.

2. COMPILATION OF THE LIST

2.1. Selection Criteria

Table 1 presents the main parameters of internal polar structures, described in the literature. The columns with respective numbers contain the following data:

- (1) the name of the galaxy;
- (2), (3) its morphological type according to the NED/RC3 and its digital code adopted from the HyperLeda database¹, ($T = -2$ corresponds to S0, $T = 0$ —to S0a, etc.). For NGC 7468, which is clearly not elliptical (as specified in the LEDA), $T = 9$ was adopted according

to Shalyapina et al. (2004);

- (4) the distance (D) in Mpc in accordance with the HyperLeda;

- (5), (6) the external radius of the polar structure in the angular and linear scales (r). In many papers the authors themselves gave this value. In other cases, we made the estimates based on the data presented in the original papers: the diagrams of radial variations of the kinematic axis position angle (PA_{kin}) or the published velocity fields. Sometimes the problem was simplified by the fact that all the ionized gas, observed at the center of the galaxy belongs to the polar structure. In this case, instead of looking for a region of the line-of-sight velocity gradient variation, it was sufficient to estimate the size of the region, occupied by the gas emission lines (for example, NGC 4552, and NGC 5129 according to the SAURON data). For some galaxies, only to the lower limit of this parameter is known, limited by the spectrograph field-of-view;

- (7), (8) the parameters of orientation of the main galactic disk: the position angle (PA_0) and the inclination to the line of sight (i_0) in degrees are in most cases taken from the original papers, and in the remaining cases—according to the HyperLeda database;

- (9) the position angle of the major axis of the bar (PA_{bar}), specified in the original papers, in degrees. In some cases, (NGC 2768, NGC 2841, NGC 6340, NGC 7217) we deal with the “triaxial bulge”, rather than the contrasting bar. For NGC 4548 we list the orientation of the internal triaxial structure instead of the external bar (in agreement with Sil'chenko (2002)). In some cases, the authors of the original papers suspected “hidden triaxiality” of the inner regions based on the indirect evidence, but could not specify the exact position angle (e.g., see NGC 3607 in Afanasiev & Sil'chenko (2007));

- (10) the major axis of the circumnuclear structure (PA_1) in degrees. It was given by the authors or estimated by us from their diagrams of radial variations $PA_{\text{kin}}(r)$. The value is missing for some galaxies, the data on the internal kinematics of which are based only on the long-slit spectroscopy (NGC 4424, NGC 4698, NGC 4941) or for which the authors have constructed the spatial model of the internal structure (Arp 220, NGC 1068, NGC 2855, NGC 3227, NGC 7049). For the NGC 3368 and NGC 4111 galaxies, the adopted parameter PA_1 significantly differs from the estimates based on PA_{kin} and was determined from the orientation of the internal dust ring. We believe that here, in the velocity field along the line of sight, we observe a superposition of two gaseous subsystems, or the inclined structure is nonstationary. For NGC 5014 the parameters of orientation were determined from the SDSS image, which reveals a narrow blue ring (Moiseev et al., 2011);

- (11) the inclination of the internal structure to the line of sight (i_1), in degrees. Evaluated the same way as PA_1 , with the same remarks on individual galaxies. Unfortunately, in many cases it is impossible to estimate this parameter, we hence either list the assumed range of

¹ <http://leda.univ-lyon1.fr>

values, or the lower limit when it is clear that the inner disk is significantly inclined (NGC 3414, NGC 7742, etc.). For NGC 2787, and NGC 2911 our own estimate of orientation of the dust structure is given;

(12) the angle of inclination Δi of the internal structure to the plane of the disk. The sign * marks the estimates from the literature, in other cases it was evaluated by us (see Section 3.4 below). For NGC 1068 and NGC 3227 the value $\Delta i > 90$ is listed, meaning that the innermost parts of the circumnuclear gaseous disks are warped so much that the orbits are re-approaching the main plane of the galaxy;

(13) the comment, pointing to the observed composition of the structure (H II—ionized, H I—neutral, CO—molecular gas, s—stars) and its structure: w—a strong warp, r—a ring, i.e. there is a hole in the center;

(14) references to the literature used.

In total, Table 1 lists 47 galaxies, for which there exist strong arguments that in their inner regions² a substantial part of the emitting matter steadily rotates in the plane, strongly inclined to the plane the main disk. As a rule, such a dynamic configuration is directly stated by the authors of papers, referred to in the last column of Table 1. In the case of other objects, we believe that the presence of polar (or highly inclined) orbits is the most reasonable explanation of the observed circumnuclear kinematics. To make this conclusion we must have a velocity field, obtained with a sufficiently high spatial resolution. Historically, the first technique was to make several spectral sections with a long slit, while more reliable results can be obtained with the panoramic (3D, integral-field) spectroscopy in the optical range, or using radio interferometry in the molecular gas lines. An interesting example is the NGC 253 galaxy, in which an IPS was revealed from the observations in the radio recombination H92 α line (Anantharamaiah & Goss, 1996).

In Krajnović et al. (2008) the terms “kinematic twist” and “kinematically decoupled component” identify the cases of significant (exceeding 10°–20°) variations of PA_{kin} with increasing distance from the center in the observed line-of-sight velocity field. Note that such a mismatch should not always be associated with rotation in orbits that lie outside the galactic disk plane. The twist of the PA_{kin} can also be related with the non-circular motions in the plane of the galaxy caused by the non-spherical potential of the central bar or triaxial bulge. Fortunately, comparing the velocity field with the results of isophote analysis of the galaxy images, we can understand what type of motion takes place (see the discussion and references in Moiseev et al. (2004)). In addition, the triaxial potential and the inclined disk should manifest themselves in different ways in the distribution of the line-of-sight velocities along the major and minor axes of the galaxy (Corsini et al., 2003). However, the absence of the

line-of-sight velocity gradient along the minor axis is not a sufficient criterion of the presence of an IPS. Hence, our list lacks plenty of candidates from Coccato et al. (2004). On the other hand, our sample includes most of the early-type galaxies from the SAURON survey, for which the difference between the PA_{kin} , determined by the velocity fields of gas and stars, is in excess of 30°. The only exception were the objects where the disk of ionized gas extends beyond the edge of the spectrograph’s field of view, obviously, being an internal part of the polar structures, observed in neutral hydrogen far beyond the stellar disk of the galaxy. This applies to NGC 2685—the prototype of the classical PRG, and a galaxy with an external UV-ring, NGC 4262 (Bettoni et al. (2010), also see Oosterloo et al. (2010) for the HI map).

In addition to the perturbing effect produced by the triaxial potential, a sharp change in the direction of the line-of-sight velocity gradient can be also due to the radial gas flows, triggered by the central burst of star formation or by a jet from the active nucleus. Thus, Coccato et al. (2004), based on the long-slit spectroscopy data suspected the existence of an IPS in NGC 6810. However, the subsequent studies have shown that the central kinematics of gas there is determined by the starburst superwind (Sharp & Bland-Hawthorn, 2010). For a similar reason we have excluded from consideration a number of known galaxies with ionization cones, in which the motions of ionized gas in the central kiloparsec region are likely to be caused by the activity of the nucleus, despite the fact that a number of authors have found inclined disks here (Mrk 3, Afanasiev & Sil’chenko (1991), NGC 5252, Morse et al. (1998), etc.).

Note that the existence of a twist of PA_{kin} is not strictly necessary. For example, in NGC 3607 and NGC 7742, visible almost face-on, the kinematic position angles for the external and internal regions are almost identical ($PA_1 \approx PA_0$). However, the amplitude of the line-of-sight velocity of gas, observed in the center is so high that the most reasonable explanation for this is rotation of the disk, strongly inclined to the line of sight. The case of an elliptical galaxy NGC 5198 is challenging. This object, according to the velocity fields, presented in Sarzi et al. (2006); Krajnović et al. (2008) has two polar structures—an internal stellar ($r < 2''$) and a more extended gaseous ($r < 5''$) structure, not coinciding with each other. At that, the position angle of the gaseous disk almost coincides with the PA_{kin} of the external regions of the stellar velocity field, however it looks that the counter-rotation occurs. But as the observed amplitude of the ionized gas rotation curve is very large, it is clearly outside the main plane of the stellar spheroid, in which the outermost gas is rotating.

2.2. Galaxies, not Included in the List

Compiling the list we have tried to review the largest possible number of observational papers on this issue.

² By inner regions we mean the scales smaller than or comparable with the characteristic scales of a bulge, or an external disk.

Table 1. List of galaxies with inner polar structures

Name (1)	Type (2)	T (3)	D , (4)	r ,'' (5)	r , (6)	PA_0 ,° (7)	i_0 ,° (8)	PA_{bar} ,° (9)	PA_1 ,° (10)	i_1 ,° (11)	Δi ,° (12)	Comm. (13)	Ref (14)
Arp 220	S?	9.3	81.3	0.3	0.12	40	40	–	–	–	90*	CO, w	Eckart & Downes (2001)
IC 1548	S0	-4.0	85.1	1.5	0.62	78	59	–	349	–	–	HII	Sil'chenko & Afanasiev (2008)
IC 1689	S0?	-2.0	67.6	10	3.28	164	90	–	74	30	90	HII+s, r	Hagen-Thorn & Reshetnikov (1995)
M 31	SA(s)b	3.0	0.78	180	0.70	35	77	–	325	40	88	CO+HII, r	Melchior & Combes (2011)
Mrk 33	Im pec?	9.9	24.2	12	1.41	116	59	–	163	47	39, 86	HII+s	Moiseev (2011)
Mrk 370	pec?	0.0	12.0	11	0.61	346	45	–	260	–	55 – 70*	HII, w	Moiseev (2011)
NGC 253	SAB(s)c	5.1	3.4	5	0.083	230	79	–	324	> 60	78 – 90	HII, r	Anantharamaiah & Goss (1996)
NGC 474	SA0 ⁰ (s)	-2.0	32.7	> 10	> 1.65	330	26	–	256	–	–	HII, r?	Sarzi et al. (2006), Krajinović et al. (2008)
NGC 1068	(R)SA(rs)b	3.0	16.1	2	0.16	278	40	48	–	–	> 90*	CO, w	Schinnerer et al. (2000b)
NGC 2217	(R)SB0 ⁺ (rs)	-0.6	20.7	3	0.30	6	21	111	20	–	90*	HII, w	Bettoni et al. (1990)
NGC 2655	SAB0/a(s)	0.1	24.2	> 15	> 1.76	85	54	90	20	–	–	HI+HII, r	Sil'chenko & Afanasiev (2004) Dumas et al. (2007) Sparke et al. (2008)
NGC 2681	(R')SAB0/a(rs)	0.4	13.2	5	0.32	148	25	25	90	–	–	HII+s	Moiseev et al. (2004)
NGC 2732	S0	-2.0	32.4	5	0.78	67	90	–	351	30 – 70	77 – 83	HII	Sil'chenko & Afanasiev (2004)
NGC 2768	E6?	-4.5	23.6	16	1.83	95	90	–	347	30 – 60	74 – 81	HII+CO	Fried & Illingworth (1994) Sil'chenko & Afanasiev (2004) Crocker et al. (2008)
NGC 2787	SB0 ⁺ (r)	-1.0	7.5	6	0.22	109	62	149	72	50	32,76	HII	Sil'chenko & Afanasiev (2004)
NGC 2841	SA(r)b?	3.0	12.6	5	0.31	150	65	154	68	–	–	HII	Sil'chenko et al. (1997) Afanasiev & Sil'chenko (1999)
NGC 2855	(R)SA0/a(rs)	-0.2	26.5	4	0.51	117	42	–	–	–	73*	HII, w	Coccato et al. (2007)
NGC 2911	SA0(s)? pec	-2.0	47.0	4	0.91	140	56	–	63	75	71,88	HII+s	Sil'chenko & Afanasiev (2004)
NGC 3227	SAB(s)a pec	1.5	18.3	0.9	0.08	158	56	138	–	–	> 90*	CO, w	Schinnerer et al. (2000a)
NGC 3368	SAB(rs)ab	2.2	13.7	3	0.20	135	48	125	35	–	–	HII	Sil'chenko et al. (2003) Moiseev et al. (2004)
NGC 3379	E1	-4.8	14.3	3	0.21	253	40	–	296	–	–	HII+s	Sil'chenko et al. (2003) Sarzi et al. (2006) Krajinović et al. (2008)
NGC 3384	SB0 ⁻ (s)?	-2.7	13.7	5	0.33	55	57	132	226	–	–	s	Sil'chenko et al. (2003)
NGC 3414	S0 pec	-2.0	25.2	9	1.10	179	52	–	68	> 60	56, 86	HII	Sil'chenko & Afanasiev (2004)
NGC 3599	SA0?	-2.0	20.3	> 7	0.69	47	28	–	335 – 290	–	40 – 60*	HII, w, r	Sil'chenko et al. (2010)
NGC 3607	SA0 ⁰ (s)?	-3.2	22.8	2	0.22	300	34	–	320	–	–	HII	Afanasiev & Sil'chenko (2007)
NGC 3608	E2	-4.8	22.9	4	0.44	255	47	–	195	–	–	HII	Afanasiev & Sil'chenko (2007)
NGC 3626	(R)SA0 ⁺ (rs)	-0.9	20.0	4	0.39	341	32	–	190	–	58, 87*	HII	Sil'chenko et al. (2010)
NGC 4100	(R')SA(rs)bc	4.1	19.7	12	1.14	346	73	–	358	60	25, 55*	HII	Fridman et al. (2005)
NGC 4111	SA0 ⁺ (r)?	-1.3	14.9	> 8	> 0.59	150	84	–	60	–	84 – 90	HII	Sil'chenko & Afanasiev (2004)
NGC 4233	S0 ⁰	-2.0	35.1	7	1.19	176	87	200	76	90	– 80	HII	Sil'chenko & Afanasiev (2004)
NGC 4424	SB(s)a?	1.0	16.8	3	0.21	95	63	–	–	–	–	HII	Coccato et al. (2005)
NGC 4548	SB(rs)b	3.1	15.6	3	0.23	145	37	110	236	–	–	HII	Sil'chenko (2002)

Table 1. (continue)

Name (1)	Type (2)	T (3)	D , (4)	r ,'' (5)	r , (6)	PA_0 ,° (7)	i_0 ,° (8)	$PA_{bar,r}$,° (9)	PA_1 ,° (10)	i_1 ,° (11)	Δi ,° (12)	Comm. (13)	Ref (14)
NGC 4552	E0-1	-4.6	15.6	5	0.38	110	14	–	32	–	–	HII	Sarzi et al. (2006), Krajnović et al. (2008)
NGC 4579	SAB(rs)b	2.9	23.6	18	2.06	96	39	58	154	–	–	HII	Dumas et al. (2007)
NGC 4672	SA(s)a pec	1.1	45.7	6	1.32	46	90	–	134	–	88 – 90	s	Bertola & Corsini (2000)
NGC 4698	SA(s)ab	1.7	16.1	5	0.39	170	74	–	–	–	–	HII+s	Pizzella et al. (2001)
NGC 4941	(R)SAB(r)ab?	2.1	21.2	2	0.21	15	37	0	–	–	–	HII	Bertola & Corsini (2000)
NGC 5014	Sa?	1.4	19.5	22	2.08	100	81	–	47	80	52 – 56	HI,r	Coccatto et al. (2005)
NGC 5198	E1-2?	-4.8	39.3	4	0.76	14	49	–	32	–	–	HII+s	Noordermeer et al. (2005)
NGC 5850	SB(r)b	3.1	38.7	6	1.13	335	37	115	35	–	–	HII	Moiseev et al. (2011)
NGC 6340	SA0/a(s)	0.4	22.4	12	1.30	70	20	85	330	40 – 60	40, 65*	HII, w	Sarzi et al. (2006)
NGC 7049	SA0 ⁰ (s)	-1.9	29.9	5	0.73	58	60	–	–	–	89*	HII	Krajnović et al. (2008)
NGC 7217	(R)SA(r)ab	2.5	16.7	3	0.24	268	30	60	329	–	–	HII+s	Moiseev et al. (2004)
NGC 7280	SAB0 ⁺ (r)	-1.3	28.2	2	0.27	258	52	60	9	> 80	68-80	HII	Sil'chenko (2000)
NGC 7468	E3? pec	9.0	31.8	6	0.92	180	45	–	120	60	49,87	HII	Chilingarian et al. (2009)
NGC 7742	SA(r)b	2.8	24.7		0.36	128	9	–	130	> 35	> 26	HII	Coccatto et al. (2007)
UGC 5600	S0?	-1.8	44.7	10	2.17	182	50	–	260	60	65, 80*	HII, w, r	Sil'chenko & Afanasiev (2000)
													Sil'chenko (2005)
													Shalyapina et al. (2004)
													Sil'chenko & Moiseev (2006)
													Shalyapina et al. (2002, 2007)

Unfortunately, the abstracts and conclusions do not always contain information on the presence of polar structures. *Therefore, we apologize in advance to the authors of papers that we may have missed.* At the same time, our sample does not include some known candidates for the presence of IPSs. Besides the already mentioned galaxies possessing extended polar disks and active nuclei with ionization cones, these are objects on which, in our opinion, the available data is insufficient or too controversial. These include: NGC 3672, mentioned in the introduction (the galaxy where the existence of an IPS was first reported), as well as most of the other galaxies with the remarkable line-of-sight velocity gradient along the minor axis from the list of Coccato et al. (2004); the kinematically decoupled nucleus in NGC 4150, known from the SAURON/OASIS data McDermid et al. (2006); NGC 7332, although having some indications of the presence of an inclined disk Sil’chenko (2005), its velocity field has a very irregular shape; NGC 524, where a polar disk was suspected (Sil’chenko, 2000), but the new data reveal a more complex structure consisting of two counter-rotating disks Katkov et al. (2011a); NGC 3367, in which according to Gabbasov et al. (2009) there is a reversal of internal isovels in the line-of-sight velocity field, but the interpretation is difficult; M83, which was suspected in the presence of an IPS from the morphology of dust lanes Sofue & Wakamatsu (1994), but the follow-up studies of perinuclear kinematics did not confirm this hypothesis.

A recent paper Davis et al. (2011) provides the data on the kinematic parameters of early-type galaxies within the ATLAS^{3D} surveys. Their lists reveal a dozen more galaxies in which the difference of position angles, measured by the velocity fields of gas and stars exceeds 40° – 50° . However, we can not be sure that we are dealing with the inner polar disks, since the authors do not give neither any $PA_{\text{kin}}(r)$ dependencies, nor the velocity fields of ionized gas. We have also eliminated from our consideration the objects in which the PA_{kin} coincides with the photometric major axis in the inner regions, and with the minor axis in the external regions (NGC 4365, NGC 4406, etc.), what is most likely related with the triaxiality of these elliptical galaxies (see the survey deZeeuw & Franx (1991))

3. STATISTICAL PROPERTIES

3.1. General Remarks

The compiled list confirms the idea that the inner polar structures are a very common phenomenon Coccato et al. (2004). Indeed, the number of known galaxies, containing IPSs is one and a half times greater than the total number of galaxies with kinematically confirmed external polar rings (about 30 objects, see Moiseev et al. (2011)). Unlike the case of “classical” PRGs, among the IPSs only relatively close objects are as yet available for detailed observations: most of galaxies from Table 1 are located closer than 30–40 Mpc from us, including three, belonging to the

Local Volume ($D < 10$ Mpc). When we mean the PRGs, it is reasonable to talk about the rings, even if they are rather wide, on the other hand, considering the IPSs, we are as a rule (in 39 out of 47, i.e. 83% of cases) talking about the disk geometry in which the inner diameter is negligible in comparison with the outer one. Unfortunately, we do not possess enough observational data of high spatial resolution to refine their detailed inner structure. As follows from Table 1, only the gaseous disks and rings are mainly found, the list contains only one galaxy (NGC 3384) with a purely stellar polar disk, and six more structures are marked as stellar-gaseous. The selection effect is present here, since methodologically it is much easier to identify the emission lines of ionized or molecular gas than to separate the absorption spectrum, observed along the line of sight, into stars, belonging to the bulge, the polar disk and the main disk of the galaxy. It is obvious that quite a few described IPSs are indeed stellar-gaseous, just that it is problematic to detect the kinematic manifestation of stars. For example, the stellar polar disk in NGC 7217, identified by its kinematic properties is remarkably more compact than the gaseous one Sil’chenko & Moiseev (2006). The ionization of gas in the IPSs can (at least partially) be explained by the ongoing star formation.

3.2. Radial scales

Figure 1 shows the histogram of distribution of the sizes of internal polar structures. It is clear that with respect to them it would be fair to use the term the “central kiloparsec”: the average median radius is about 600 pc, 85% of all IPSs are sized below 1.5 kpc. This compactness is likely due to the fact that for a stable existence of polar orbits a stabilizing factor is required, i.e. a spheroidal or triaxial potential. For the classical PRGs it is the gravitational potential of dark halos, and for the internal structures—the potential of a bulge or a bar (see Section 3.5 below). This may practically explain the lack of known polar structures of intermediate size, with $r = 2$ – 10 kpc. Evidently, at these scales, the differential precession that occurs under the influence of gravitational potential of the stellar disk leads to a catastrophically fast decrease of orbit inclinations and their “fallout onto the disk.” Note that even in the IPS in IC 1689—the largest in our list—the radius is smaller than the effective radius of the bulge ($r_e = 4$ kpc according to Reshetnikov et al. (1995)). It is possible that it is exactly the picture, observed in NGC 7743—a lenticular galaxy where the entire ionized gas at $r = 1.5$ – 5.4 kpc is located in the plane, inclined by 34° or 77° with respect to the stellar disk Katkov et al. (2011b).

The dip in the distribution for $r < 200$ pc is apparently caused by the limited spatial resolution of most of observations, since this scale at $D = 30$ Mpc corresponds to an angular size of about $2''$.

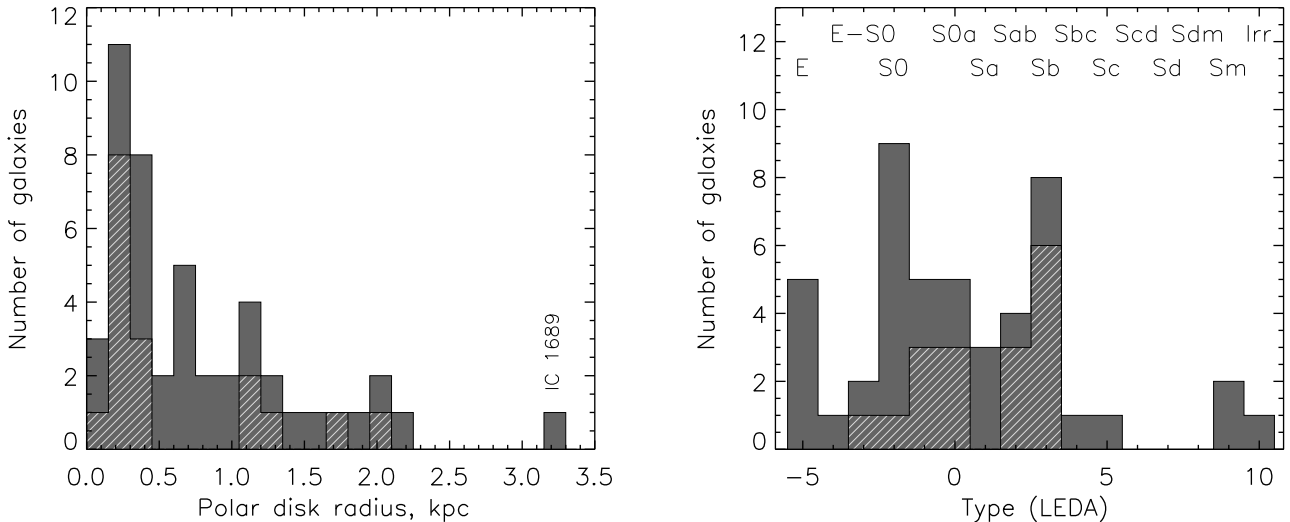


Fig. 1. The histograms of distribution of the internal polar structures by sizes (left) and morphological types of galaxies (right). All the sample are marked in gray, while the galaxies with bars and triaxial bulges are shaded.

3.3. Morphological Types

We know that the outer polar rings are as a rule observed around the early-type galaxies, E/S0 (Whitmore (1991); Reshetnikov et al. (2011)). One of the explanations for this is that these galaxies have poor own internal gas reserves, hence the gas clouds at the polar orbits do not undergo any collisions with the gas in the main galactic plane. To what extent is this true for the internal polar structures? The estimates made by Coccato et al. (2004) have shown that the remarkable line-of-sight velocity gradient of gas along the minor axes of galaxies is predominantly observed in the S0 galaxies and early-type spirals, which may indicate that there is a relation between this phenomenon and the presence of a vigorous bulge. However, the authors themselves noted that the velocity gradients along the minor axis are not always due to rotation in the polar plane.

If we consider only the galaxies with confirmed IPSs, the distribution by morphological type becomes broader (Fig. 1, right). The median average here is $T = 0$, i.e. only a half of all galaxies belongs to the S0a type and earlier. And nearly a third of them are the Sb-type objects and later, even including a few Sm and Irr galaxies, commonly possessing small bulges. Note that the actual number of late-type galaxies must be underestimated by the selection effect, since the large surveys of kinematics of the circumnuclear regions with the MPFS and SAURON integral-field-spectrographs were focused primarily on the E/S0 galaxies.

Therefore, we can make a preliminary conclusion that for the existence of a circumnuclear polar or inclined disk, the morphological type of a galaxy is less significant than for the PRG. Apparently, the effect of collision of gas at the polar orbits with the gas of the main disk is not critical

for the formation of these structures. It is possible that the forming inner polar disk has time to preliminarily “sweep up” the region of the central kiloparsec. In any case, the examples of strongly warped IPSs are known, when the gas near the nucleus rotates in the polar plane, and with increasing distance from the center, the orbits fall into the plane of the galaxy (see Section 3.4 below). It is possible that in some cases the inclined orbits are occupied by the gas from the main plane of the galaxy under the effect of the gravitational potential of the bar (Section 3.5). Note, however, that the histograms in Fig. 1 do not show any significant differences in the distribution of barred galaxies.

3.4. Inclined or Polar?

Using the term “polar” with respect to the IPSs, one has to remember that is not always possible to accurately measure the inclination of the plane of the inner disk to the outer. It is easy to show (Moiseev (2008)) that this angle Δi is expressed by the relation:

$$\cos \Delta i = \pm \cos(PA_0 - PA_1) \sin i_0 \sin i_1 + \cos i_0 \cos i_1. \quad (1)$$

Most often we only know the parameters of orientation of the outer disk (PA_0, i_0) and the direction of the major axis of the inner structure PA_1 . However, to determine the inclination angle i_1 of the orbits to the line of sight from the observed kinematics within the model of circular rotation, a detailed velocity field with a large number of independent points is required. Moreover, a stable solution can usually be obtained only for a notable inclination of the disk to the line of sight ($i_1 > 30-40^\circ$). An only exception is a case of a purely polar disk in a galaxy, seen

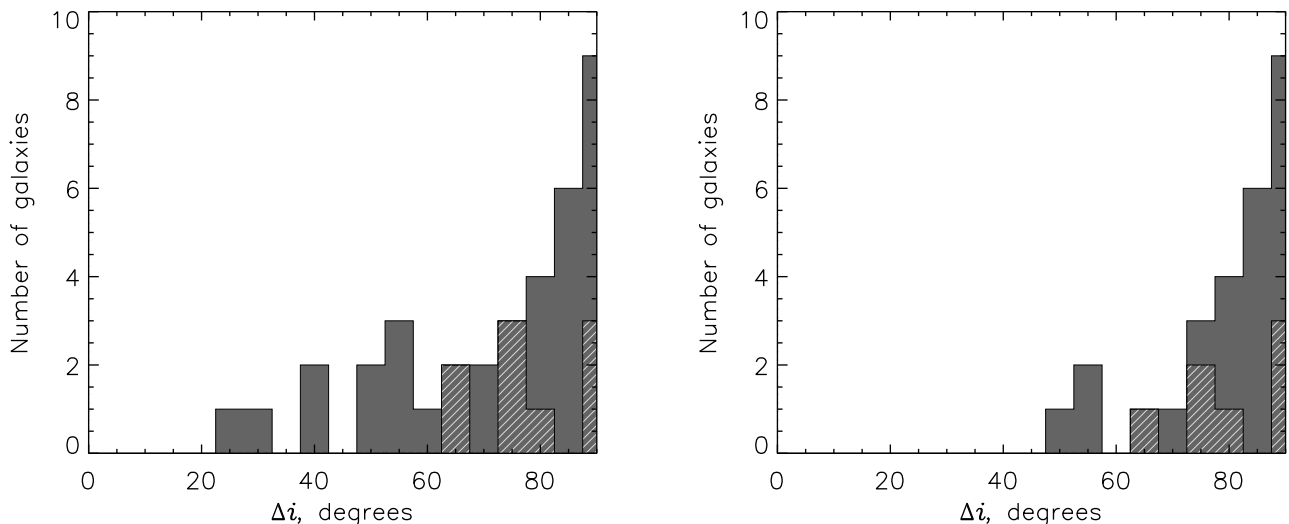


Fig. 2. The distribution by the inclination angle of inner rings and disks to the main galactic disk. The left plot: the entire possible range of solutions for Δi from (1), the right plot: in the case of two solutions the greater was taken. All the galaxies are marked in gray, while the galaxies with bars and triaxial bulges are shaded.

edge-on ($PA_0 = PA_1 + 90^\circ$, $i_0 = 90^\circ$). The uncertainty with the sign of the first term in (1) is due to the fact that PA and i do not fully characterize the position of the plane with respect to the observer—we also need to know the direction of the moment of rotation, i.e. which side of the disk is nearer to us, and which is farther. Hence, for a number of galaxies with $i_0 < 90^\circ$ Table 1 gives both possible alternate solutions of (1). One of the few exceptions is the polar ring in the Andromeda galaxy (M31). Its relatively large angular scale has allowed the authors of Melchior & Combes (2011) to precisely understand how it is oriented with respect to the galactic disk.

The angle Δi was estimated for 27 objects, which is slightly over a half of the entire sample. The histograms presented in Fig. 2 resemble much the distribution by the same parameter of the outer polar rings from Whitmore (1991). Notwithstanding the above uncertainty with the estimation of Δi , most of the outer inclined structures turn out to be truly polar, i.e. perpendicular to the outer disks of galaxies. Thus, $\Delta i > 70^\circ$ in 23 out of 27 (i.e. 85%) cases.

On the other hand, even if we choose between the two solutions for Δi the option, closest to 90° (Fig. 2, right), there are still IPSs located at a more moderate angle Δi equal to 50° – 60° : NGC 3599, NGC 5014 and NGC 6340. Such structures are unlikely to be stable: they have to relatively quickly fall into the galactic plane under the effect of differential precession. An indirect indication of this are the observed warps of gaseous disks in NGC 3599, and NGC 6340. Note that similar warps are found in seven galaxies of the sample. In many cases, the authors can construct a detailed spatial model of such warped disks, reproducing not only the kinematics, but also the bright-

ness distribution of ionized (NGC 2855, and NGC 7049) or molecular (Arp 220, NGC 1068, NGC 3227) gas (see references in Table 1).

3.5. Bars and Triaxial Bulges

The relationships of internal polar structures with the nonaxisymmetric gravitational potential have been widely discussed in the literature, starting from the paper Bettoni et al. (1990), for the first time describing the case of a circumnuclear polar disk in a barred galaxy NGC 2217, oriented virtually perpendicular to the major axis of the bar. Further on, similar arrangements of IPSs were found in many other barred galaxies, listed in Table 1. It was repeatedly noted that such an arrangement of the polar disk along the smallest section of the bar—i.e. in one of the main planes of a triaxial potential—has to be stable. At that, it is sufficient to have a non-spherical (triaxial) bulge in a galaxy instead of a large-scale bar (Sil’chenko, 2000; Afanasiev & Sil’chenko, 1999; Corsini et al., 2003).

Figure 3 presents the distribution of all our sample galaxies by the angle $\Delta\psi$ between the major axis of the nonaxisymmetric stellar structure (a bar or a triaxial bulge) and the major axis of the IPS (projected on the galactic plane):

$$\Delta\psi = \arctan \frac{\sin(PA_{\text{bar}} - PA_0) \cos i_0}{\cos(PA_{\text{bar}} - PA_0)} - \arctan \frac{\sin(PA_1 - PA_0) \cos i_0}{\cos(PA_1 - PA_0)}. \quad (2)$$

Despite the relatively small statistics available, the tendency of polar structures to align orthogonally to the

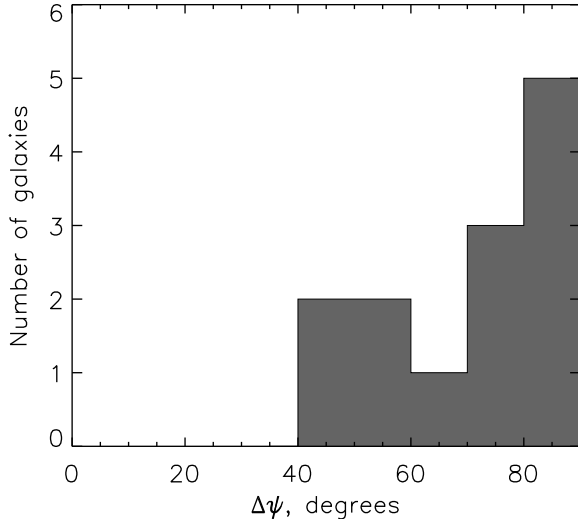


Fig. 3. The distributions by the angle between the major axis of the polar disk and the bar (or the triaxial bulge).

major axis of the bar ($\Delta\psi = 90^\circ$) is clearly visible. So far, the literature has detailed calculations of the formation of such inner disks, for instance, via the capture of the outer gas clouds with the corresponding direction of the orbital moment. Usually the authors use a star-dynamic analogy with polar or warped disks, observed in the global triaxial potential of elliptical galaxies (see discussion in Corsini et al. (2003) and Sil’chenko & Afanasiev (2004)). In any case, it is most likely that triaxiality of the potential is responsible for the stabilization of the internal polar disks in the circumnuclear regions of elliptical galaxies (NGC 3608, NGC 4552, etc.). Besides the scenario with the capture of gas clouds with the corresponding orbital moment, the studies Sofue & Wakamatsu (1994) and Friedli & Benz (1993) are often quoted. The authors of the former paper made an assumption that the internal polar disk formed under action of the gravitational potential of the bar on the warped gaseous disk of the galaxy. This leads to the loss of angular momentum in the azimuthal plane and its conservation in the polar plane. Friedli & Benz (1993) have demonstrated with the aid of a three-dimensional numerical model that if a part of gas in the disk of a galaxy initially rotated in the opposite direction with respect to the rest of the disk, in the process of secular evolution of the bar the gas clouds occupy stable orbits, strongly inclined to the galactic plane. Olga Sil’chenko and her colleagues have repeatedly emphasized in their numerous papers the cases of simultaneous observations of polar disks in the inner regions of galaxies and the counter-rotation of gas–stars or stars–stars in the outer regions. This feature is detected in 9 galaxies of our list (see the following section). The initial counter-rotating component is most likely the result of absorption of a dwarf companion. Note two points, however. Firstly, in

the modeling made by Friedli & Benz (1993), the obtained disk is not polar, but inclined at about 45° to the plane of the galaxy. Secondly, the proposed mechanisms can obviously not be the main method of polar disk formation, since in this case one should expect an increased number of bars in the galaxies with IPSs. However, out of 40 disk galaxies (S0-type and later) from our sample only 17 possess confirmed bars or triaxial bulges³, which is $43 \pm 8\%$ or $33 \pm 7\%$, if we ignore the non-spherical bulges⁴. This is in good agreement with the known frequency of bars in nearby galaxies, which is about 45% (Aguerri et al., 2009).

Therefore, we must conclude that although the bars have an effect on the orientation of polar disks, the existence of a triaxial potential is not absolutely necessary for the existence of IPSs. Surely, the galaxies may have a certain internal triaxiality, barely noticeable to the detached observer (see, e.g., the discussion of this issue in Afanasiev & Sil’chenko (2007)). However, the circumnuclear regions usually look more symmetrical than the outer ones not only in the unbarred galaxies, but also in the barred spirals (inside the Lindblad resonances of the bar). In Sil’chenko et al. (2010), we show that NGC 3599 and NGC 3626 have an internal “oval distortion of the disk”, which may point to the formerly existing bars, destroyed in the process of secular evolution or under the effect of external influence. However, such a scenario is unlikely to fit most of the remaining unbarred galaxies.

3.6. External Environment

Another frequently debated issue is the relationship of IPSs with the external environment of galaxies, and the processes of their interaction. By analogy with external polar rings, it is reasonable to expect that the circumnuclear polar structures can as well be formed as a result of the capture of matter (gas clouds or a dwarf companion) with the orbital momentum, orthogonal to the moment of rotation of the galactic disk. Typically, such discussions considered individual cases, where there are either clear signs of a recent interaction, or vice versa—a galaxy is isolated and looks unperturbed by any external effects. The examples of an explicit relation of IPSs with the environment are: NGC 2655 (Sparke et al., 2008), where the polar disk of ionized gas is an internal part of a strongly warped extended disk of neutral hydrogen with pronounced tidal structures in the outer regions, low-contrast ripples on the optical images of NGC 474 (Arp, 1966) and NGC 6340 (Zasov et al., 2008; Chilingarian et al., 2009),

³ Table 1 lists angle PA_{bar} for all the galaxies, where we managed to find references on the presence of an internal triaxial structure. We mainly focused on the studies devoted to a detailed analysis of the morphology of galaxies (including those using the images in the near-IR, optimal for the search of bars). We believe that such an approach is more correct than the use of a morphological classification from RC3/NED.

⁴ Hereinafter the variance of the binomial distribution is specified as an error.

Table 2. Signs of effects introduced by the environment

Name (1)	Optical (2)	HI (3)	counter-rotation (4)
Arp 220	Arp (1966)		
IC 1548			Sil’chenko & Afanasiev (2008)
IC 1689	Reshetnikov et al. (1995)		
M 31	Ibata et al. (2004)	Braun et al. (2009)	
Mrk 33		Bravo-Alfaro et al. (2004)	
NGC 253	Davidge (2010)		Anantharamaiah & Goss (1996)
NGC 474	Arp (1966)		
NGC 2655	Sparke et al. (2008)	Sparke et al. (2008)	
NGC 2681	Cappellari et al. (2001)		
NGC 2768		Morganti et al. (2006)	
NGC 2787		Shostak (1987)	
NGC 2841			Afanasiev & Sil’chenko (1999)
NGC 2855	Corsini et al. (2002)		
NGC 3227	Arp (1966)		
NGC 3368		Schneider (1989)	
NGC 3379		Schneider (1989)	
NGC 3384		Schneider (1989)	
NGC 3414		Morganti et al. (2006)	Sil’chenko & Afanasiev (2004)
NGC 3607		Oosterloo et al. (2010)	
NGC 3608		Oosterloo et al. (2010)	Jedrzejewski & Schechter (1988)
NGC 3626			Ciri et al. (1995)
NGC 4111		Serra et al. (2012)	
NGC 4424	Cortés et al. (2006)	Chung et al. (2007)	
NGC 4672	deGrijs & Peletier (2000)		
NGC 4698		Chung et al. (2009)	
NGC 5014		Noordermeer et al. (2005)	
NGC 5850	Higdon et al. (1998)		
NGC 6340	Zasov et al. (2008); Chilingarian et al. (2009)		
NGC 7217			Merrifield & KuijkenK (1994)
NGC 7280			Afanasiev & Sil’chenko (2000)
NGC 7468	Evstigneeva (2000)		
NGC 7742			Sil’chenko & Moiseev (2006)
UGC 5600	Shalyapina et al. (2007)		

the existence of two kinematic HI components with different laws of rotation in NGC 3414 (Morganti et al., 2006).

An example of an integrated approach to the problem is a recent paper, devoted to the statistics of the differences in the kinematics of gas and stars in the ATLAS^{3D} Davis et al. (2011) survey, performed with the SAURON integral-field spectrograph. However, firstly, these results only relate to the early-type galaxies, and secondly, as we have already noted above, not every case of “kinematic misalignment” indicates rotation at polar or inclined orbits.

Table 2 contains the data on the galaxies of our sample, for which there is evidence of a recent (on the scale of less than 1–2 Gyr) interaction. Column (1) gives the name of the galaxy, (2) bears references to papers, indicating interaction with a companion or a merger of a satellite based on the optical photometry data, (3) gives indications of tidal structures or nearby clouds, observed in HI, (4) contains an indication of the presence of a counter-rotating component in the galactic disk. In total such evidence were collected for 33 galaxies, making up $70 \pm 7\%$ of the entire IPS sample. Such a high proportion of galaxies with signs

of recent interaction allows us to conclude that the effects of external environment do indeed play a major role in the formation of internal polar rings and disks.

4. SUMMARY AND CONCLUSIONS

We compiled the list of galaxies with polar (or strongly inclined to the main the galactic plane) disks and rings detected in their inner regions. It is interesting to note that more than a half (60%) of described structures have been discovered or confirmed as a result of observations at the SAO RAS 6-m BTA telescope using the MPFS integral-field spectrograph, or the SCORPIO instrument in the scanning Fabry-Perot interferometer mode. The study of statistical properties of various parameters, characterizing these inner structures allows us to draw the following conclusions.

1. The stellar-gaseous polar disks and rings are found in the central regions of galaxies of all morphological types.

2. The vast majority of inner polar structures have the radius of less than 1.5 kpc. This limitation can be associated with the stabilizing role of the bulge.
3. The innermost regions of these structures are as a rule located in the polar plane, while farther from the nucleus we frequently observe a warp—the orbits approaching the galactic plane.
4. The inner polar structures are equally common in galaxies with and without bars. At the same time, if galaxy has a bar (or a triaxial bulge), this leads to the stabilization of the polar disk so that its axis of rotation coincides with the major axis of the bar.
5. Seventy percent of galaxies with inner polar structures reveal signs of a recent interaction, pointing to the leading role of the external environment in the formation of these peculiar structures.

It is as yet difficult to estimate the frequency of occurrence of circumnuclear polar disks, since our sample is composed from very heterogeneous sources. We can only conclude that since the number of such galaxies is one and a half times greater than the number of kinematically confirmed PRGs, and they are on the average located much closer, their fraction among the fairly bright galaxies should significantly exceed the known estimates of the occurrence of PRGs Whitmore et al. (1990); Reshetnikov et al. (2011) and amount to at least 3–5%. It is possible that a careful analysis of kinematics of all the galaxies from the ATLAS^{3D} survey, instead of the early-type galaxies alone (as in Davis et al. (2011)) will allow to give much more accurate estimates of the fraction of galaxies with IPSs.

In contrast to the external large-scale polar rings, in which the numerical modelling succeeds to reproduce the main stages of formation (see examples and references in Bournaud & Combes (2003); Combes (2006)), such modelling has not yet been performed for the internal structures. However, the provided statistics of the IPS properties indicates that just like the classical PRGs, the vast majority of internal polar rings and disks were formed as a result of capture of matter from the external environment of galaxies. Moreover, in a recent work Sil'chenko et al. (2011) the authors, using models grids from the GalMer database, have demonstrated that as a result of interaction of a giant S0 galaxy with a dwarf companion rich in gas, a ring of star formation has formed in the bulge region, strongly inclined to the plane of the galaxy. The companion mass ratio is 1 : 10, i.e. it corresponds to the minor merging events. Specific conditions of interaction have to be satisfied, the companion must initially be at the orbit with the retrograde motions, while the planes of disks of both companions have to be nearly orthogonal. We hope that the development of such models will allow to better conceive the processes of formation of IPSs in particular galaxies and reproduce their observed parameters.

We should not be confused by the lack of visible signs of recent interaction in approximately 1/3 of galax-

ies from the list. Firstly, sufficiently deep optical images and HI distributions are not available for all the galaxies. Secondly, it is possible that some time after the interaction with a dwarf companion, the presence of matter at polar orbits of the inner part of the galaxy may turn out to be the only evidence of this event. It is therefore important to study the stability of internal polar orbits in the real gravitational field of galaxies, comprising the contribution of the disk, bulge, bar and halo. It would be interesting to know whether our preliminary assumption of the absence of stable structures of intermediate size between the central kiloparsec region and the outer boundary of the stellar disk is indeed true (Section 3.2).

In principle, in some cases it is possible to form an IPS even without the interaction with the environment. For example, it is demonstrated in Schinnerer et al. (2000a,b) that compact (about 100 pc) disks of molecular gas in the circumnuclear regions of NGC 1068 and NGC 3227 could become strongly warped under the effect of the ionization cone and radiation pressure from the active nucleus. However, this scenario is clearly not suitable for most of galaxies with more extended polar disks and rings.

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